NUMERICAL SIMULATION OF RELATIVISTIC ELECTRON BEAM GENERATION WITH A FOIL DIODE

Raymond W. Lemke

Simulators and Advanced Weapons Concepts Branch
Air Force Weapons Laboratory
Kirtland Air Force Base, New Mexico 87117

Abstract

Atmospheric propagation experiments at the Air Force Weapons Laboratory utilize a 150 KA, 6 MV relativistic electron beam produced by field emission in a foil diode. To characterize the beam for the experiments requires an understanding of beam formation in the diode. To this end CCUBE, a sophisticated two-dimensional, time dependent, particle-in-cell code developed at Los Alamos National Laboratory, has been used to simulate electron beam generation in a foil diode. Simulation results for two different cathode tip geometries are discussed. Comparisons with experiment are made.

Introduction

The PR1590 is a Marx device in which a 26Ω Blumlein pulse-forming line (PFL) is charged to 6 MV. Transferring the Blumlein energy to a diode yields a 150 ns long annular electron beam with a current of 150 KA and energy of 6 MeV/electron. For the purpose of performing propagation experiments, the relativistic electron beam (REB) is injected into a drift chamber which typically contains low density air. To characterize the REB used in our propagation experiments CCUBE[1,2], an axisymmetric, electromagnetic, particle-in-cell code has been used to simulate beam formation in the PR1590 diode.

It was not economically practical to simulate the actual pulse-forming problem because of the long pulse length. Thus, in the simulations the diode voltage rises to 6 MV in 20 ns. The simulation results presented in this paper are for the diode geometry depicted in Fig. 1. Other diode geometries were simulated, but the results are qualitatively similar and are not presented here.

The simulations produced a 1 cm thick annular REB with an inner radius of 7.8 cm and peak current density of 1.3 KA/cm^2. An impedance mismatch in the computer simulation resulted in a lower voltage, lower current, and larger beam radius than observed experimentally. However, the beam structure agrees qualitatively with experimental observations. The current flow in the diode is shown to be load limited. The peak diode current agrees with analytic predictions.

PR1590 Diode Simulation and Results

The simulation geometry is depicted in Fig. 1. In Fig. 1, the conductors in the problem are indicated by the letters CS (cathode shank), CT (cathode tip), A (anode), and DW (inner diode wall) with radii of 1.25 cm, 2.50 cm, 10.00 cm, and 10.00 cm, respectively. The gap between CT and A is 6.0 cm. All of the conductors are assumed to be perfectly conducting. Any charge that reaches either DW or A is absorbed.

CCUBE simulates diode emission in the following manner.[2] A transverse electromagnetic wave (TEM) of specified amplitude is launched from the left-hand boundary in Fig. 1 and propagates toward the anode along the coaxial transmission line formed by CS, CT, and DW. The TEM wave amplitude corresponds to a source impedance that is matched to the impedance of the geometrical configuration at the left-hand boundary. When the TEM wave amplitude reaches a specified threshold value at any point on CS or CT, charge is emitted at a rate that cancels out the normal component of the electric field at the emitting point. Thus, the emission is space-charge limited.[3]

The impedance at the left-hand boundary in Fig. 1, the effective source impedance, is 120Ω. This is four times larger than the actual PR1590 PFL impedance, the value of which has been matched to the diode load impedance to yield maximum voltage. Because of the mismatch, CCUBE self-consistently calculated voltage and current histories with magnitudes lower than observed experimentally. The voltage and current histories obtained from the simulation for the geometry of Fig. 1 are shown in Fig. 2. The voltage corresponding to matched source-load impedances is also shown in Fig. 2. Matching of the source and diode load impedances can be accomplished by not allowing the first few cells along CS to emit and, if necessary, by modifying the geometry at the left-hand boundary. Figures 3a through 3d, particle plots produced by CCUBE summarizing the development of the REB in the PR1590 diode, can be used to explain the structure present in the time history of the generated beam current shown in Fig. 2. As shown in Fig. 3a, at 4.0 ns particles comprising the beam current exiting the anode are being emitted from the top of the cathode tip face. Particles emitted elsewhere stream toward the inner diode wall because of the radial electric force associated with the TEM wave. Note that the jagged sloping region of the cathode tip is, for the simulation, comprised of a number of steps one axial step size wide and one radial step size high. In reality this region is smooth. Field enhancement at the step corners did not result in excessive emission from this region. As more particles are emitted from behind the cathode tip face and stream to the diode wall (Fig. 3b), the cathode tip becomes screened by the charge stream and the field at this point levels off somewhat. A corresponding current plateau is observed in Fig. 2 between 5.0 ns and 10.0 ns. By 14.0 ns (Fig. 3c) the current flowing in the diode is large enough such that the associated magnetic field cuts off flow from the cathode shank. The diode current is now dominated by charge emitted from the lateral surface of the cathode tip. The magnetic force is large enough to allow charges emitted from the cathode tip to reach the anode and exit as part of the REB. As can be seen in Fig. 2, the beam current at the anode rises rapidly until all charge flowing off the cathode reaches the anode. As the voltage levels off so does the current (Fig. 2). By 22.0 ns (Fig. 3d) the voltage and current have reached the steady state values of 3.8 MV and 66 KA, respectively. Charge flow from the cathode shank has been magnetically cut off, and the diode flow is seen to be load limited. Also exhibited in Fig. 3d is a bifilar beam

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14. ABSTRACT
Atmospheric propagation experiments at the Air Force Weapons Laboratory utilize a 150 KA, 6 MV relativistic electron beam produced by field emission in a foil diode. To characterize the beam for the experiments requires an understanding of beam formation in the diode. To this end CCUBE, a sophisticated two-dimensional, time dependent, particle-in-cell code developed at Los Alamos National Laboratory, has been used to simulate electron beam generation in a foil diode. Simulation results for two different cathode tip geometries are discussed. Comparisons with experiment are made.

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structure. Most of the beam charge is confined in a 1 cm thick annulus with an inner radius of 7.8 cm. As can be seen in Fig. 3d, at the anode the REB has a central core of radius 2.5 cm consisting of charge emitted from the cathode tip face. Multiple structures have been observed experimentally in the REB generated in the PR1590 diode. Fig. 4 is a photograph of a cellophane witness foil placed at the exit port of the PR1590 diode (to the right of the anode in Fig. 1) for one shot. The aforementioned bifilar structure is made evident by the burn patterns in the cellophane.

Comparison of Simulation Results With Analytic Theory

In this section the theory of magnetic cutoff in high current diodes is used to obtain a value for the peak diode current corresponding to the flow of Fig. 3d.

For magnetic cutoff of flow in a high current diode, Creedon[4] has shown that the peak diode current is given by

$$I_o = gI_\alpha \gamma_m \{\ln[\gamma_m + (\gamma_m^2-1)^{\frac{1}{2}}] + \frac{\gamma_o - \gamma_m}{(\gamma_m^2-1)^{\frac{1}{2}}}\} \quad (1)$$

where γ_m corresponds to the voltage at the extent of the flow, γ_o corresponds to the peak diode voltage, I_α = 8.5 KA, and g is a geometrical factor which is related to the diode impedance.[5] As can be seen in Fig. 3d, the flow which has been magnetically cut off is confined to the cathode shank surface in a sheath approximately 0.3 cm thick. The edge of the sheath corresponds to the extent of the flow; and hence, to the position at which γ_m should be evaluated. The appropriate values of γ_m and γ_o, graphically estimated from the CCUBE simulation results, are 1.1 and 8.4, respectively. The value of g corresponding to the geometry in Fig. 3d is 0.48.[6] Substituting these values into Eq. (1) yields a peak total diode current (I_o) of 73 KA. The simulation value of I_o is 66 KA. Despite the fact that Eq. (1) was derived for one-dimensional flow, the analytical and numerical values of I_o agree to within 10 percent.

Summary

The simulation results indicate that during the voltage risetime a significant amount of charge flowing off the cathode is lost to the inner diode wall due to insufficient magnetic insulation. Because of a mismatch in the source-diode, impedance, the simulation produced a beam with lower current, lower energy, and larger radius than observed experimentally. The beam structure agrees qualitatively with experimental observations. The diode flow was shown to be load limited. The value of the peak diode current obtained from analytic theory agreed with the simulation result to within 10 percent.

Acknowledgments

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[5]J. M. Creedon, J. Appl. Phys., Vol. 46, No. 7, July 1975, p. 2946.

[6]$g = [\ln (R_2/R_1)]^{-1}$. For the geometry under consideration, the appropriate values of R_2 and R_1 are 10.0 cm (the inner radius of the diode wall) and 1.25 cm (the radius of the cathode shank), respectively. See Ref. 5.

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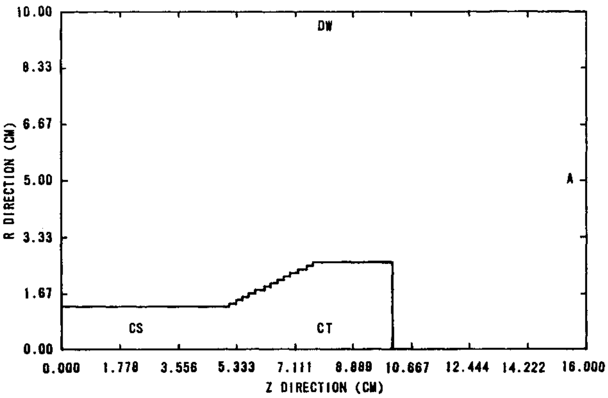

Fig. 1. Simulation geometry for the PR1590 diode.

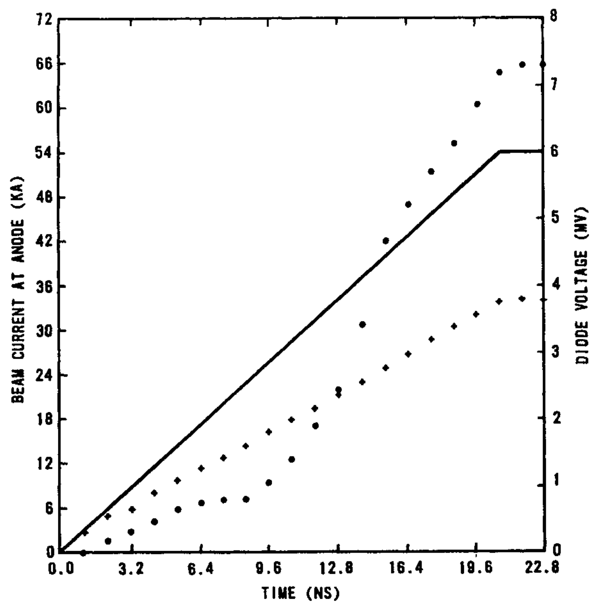

Fig. 2. CCUBE voltage and current histories:
..... = beam current at anode;
+++++ = simulation diode voltage;
——— = voltage for matched source-load impedances.

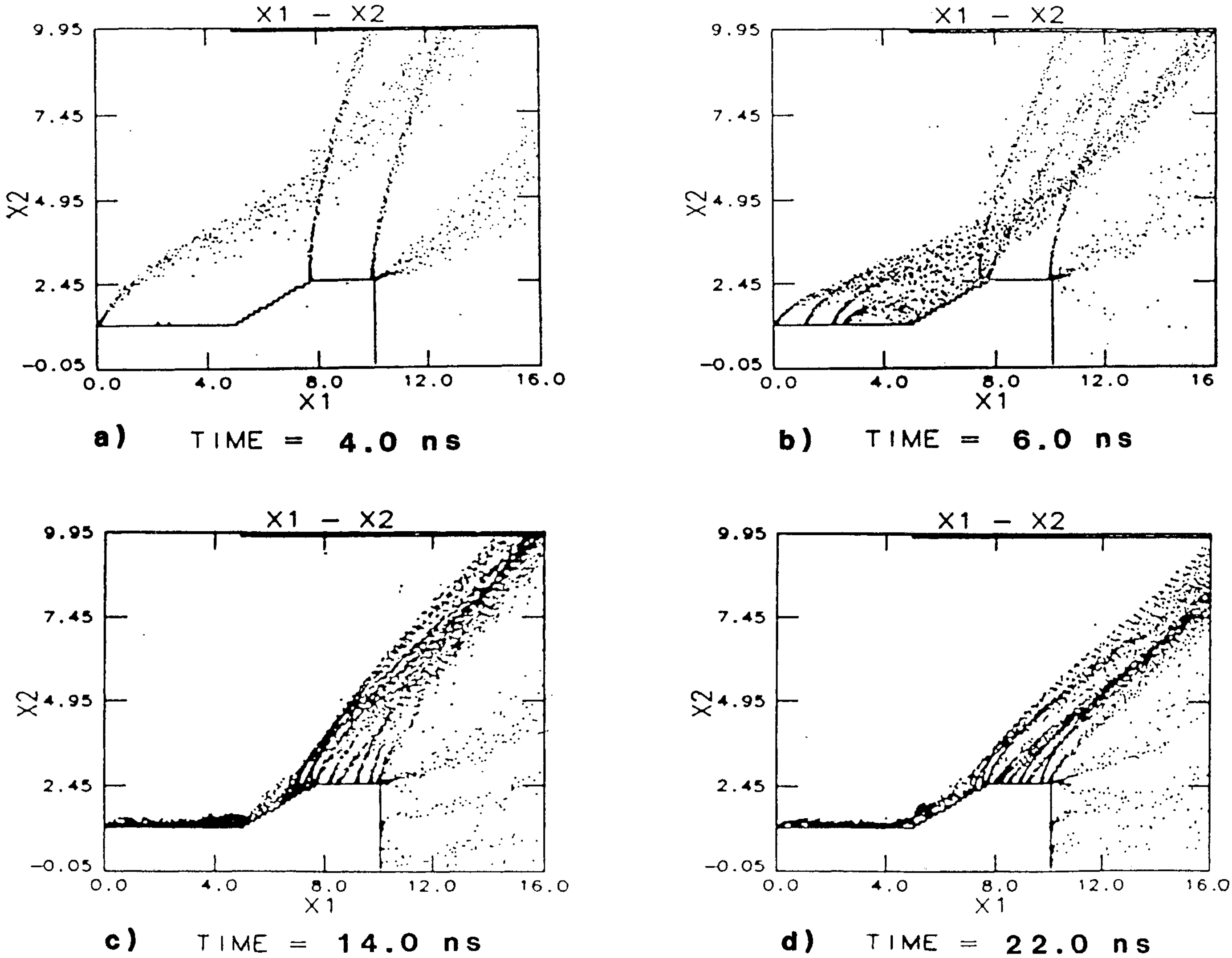

Fig. 3. CCUBE particle plots showing state of beam formation at time = 4.0 ns, 6.0 ns, 14.0 ns, and 22.0 ns. X2 and X1 represent the r and z coordinates, respectively.

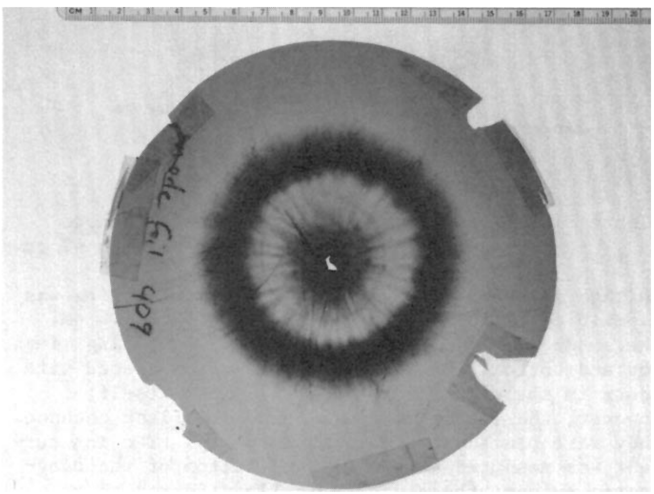

Fig. 4. Signature left by PR1590 beam on a cellophane witness foil placed at exit port of diode during one shot.